Study 2a neutrino-factory front-end design

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We describe a new front end design for a neutrino factory. This design, denoted as Study 2a, was done as part of the APS study on the physics of neutrinos. The channel is 295 m long and produces 0.17 μ/p into the accelerator transverse acceptance of 30 mm and longitudinal acceptance of 150 mm.

1. INTRODUCTION

A detailed design [1] for a front end of a neutrino factory was given in the U.S. Muon Collaborations second feasibility study (FS2). With a 1 MW proton driver the front end produced 0.17 μ/p into an accelerator transverse acceptance of 15 mm and longitudinal acceptance of 150 mm. However, the front end was very expensive and subsequent simulation R&D has been devoted to finding a new configuration that could produce the same number of useable muons at less cost. The idea for the adiabatic buncher was developed as part of this effort [2]. This new concept replaces the induction linacs and fixed frequency *rf* bunching cavities in FS2 with a string of varying frequency *rf* cavities. It was also realized that the accelerator transverse acceptance could be increased from 15 to 30 mm for a moderate increase in cost. This allowed a much simpler and shorter cooling channel to be designed, which gave the same number of muons in the new accelerator acceptance. These ideas were incorporated into a new design, which we call Study 2a, as part of the 2004 APS study on the physics of neutrinos [3].

The overall layout of the front end was originally designed by R. Palmer [4]. During the course of Study 2a the design was made more realistic [5] by generating the field from a single table of coils, carefully matching the fields at geometrical boundaries, studying optimized collection field profiles, adding a tapered beampipe in the collection region, adding *rf* windows in the buncher, discretizing the *rf* frequencies, setting the cooler *rf* frequency to 201.25 MHz, adding Be coating over the LiH absorbers, and generating new MARS [6] beam distributions. The final layout is shown schematically in Fig. 1.

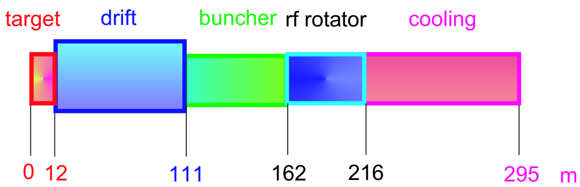

Figure 1. Schematic layout of Study 2a front end.

The first ≈12 m is used to capture pions produced in the target. The radial aperture of the beam pipe increases from 7.5 cm at the target up to 25 cm. Next comes ≈100 m for the pions to decay into muons and for the energy-time correlation to develop. The adiabatic bunching occupies

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the next ≈50 m and the phase rotation ≈50 m following that. Lastly, the channel has ≈80 m of ionization cooling. The total length of the new front end is 295 m.

Focusing in the front end is accomplished by using 460 solenoid coils. The on-axis field falls very rapidly in the collection region to a value of 1.75 T. It keeps this value with very little ripple over the decay, buncher and rotator regions. In a short matching section at the end of the rotator, the 1.75 T field is changed to the alternating field used in the cooler.

2. SIMULATION DETAILS

The target arrangement for Study 2a was identical to that used in FS2. A 24 GeV proton beam was assumed to be incident on a pulsed mercury jet. The interaction takes place inside a 20 T solenoidal field.

Most of the 75 cm buncher cell length is occupied by the 50-cm-long *rf* cavity. The cavity iris is covered with a Be window. The limiting radial aperture in the cell is determined by the 25 cm radius of the window. The window thickness varied from 200 to 395 μm. The 50-cm-long solenoid was placed outside the *rf* cavity in order to decrease the magnetic field ripple on the axis and minimize beam losses from momentum stop bands. The buncher section contains 27 cavities with 13 discrete frequencies and gradients varying from 5-10 MV/m. The frequencies decrease from 333 to 234 MHz in the buncher region. The cavities are not equally spaced. Fewer cavities are used at the beginning where the required gradients are small.

The rotator cell is very similar to the buncher cell. The major difference is the use of tapered Be windows on the cavities because of the higher *rf* gradient. The window thickness near the beam axis was 750 μm. There are 72 cavities in the rotator region, with 15 different frequencies. The frequencies decrease from 232 to 201 MHz in this part of the front end. All cavities have a gradient of 12.5 MV/m. The energy spread in the beam is significantly reduced.

Much of the cost savings in the present study comes from the simplified cooling lattice. One half-cell of the channel is shown in Fig. 2. The cooling channel was designed to have a relatively flat transverse beta function with a magnitude of about 80 cm. Most of the 150 cm cell length is taken up by the 50-cm-long *rf* cavities. The cavities have a frequency of 201.25 MHz and a gradient of 15.25 MV/m. A novel aspect of this design comes from using the windows on the *rf* cavity as the cooling absorbers. This is possible because the near constant beta function does not significantly increase the emittance heating at the window location. The window consists of a 1 cm thickness of LiH with 25 μm thick Be coatings. The alternating 2.8 T solenoidal field is produced with one solenoid per half cell, located between the *rf* cavities.

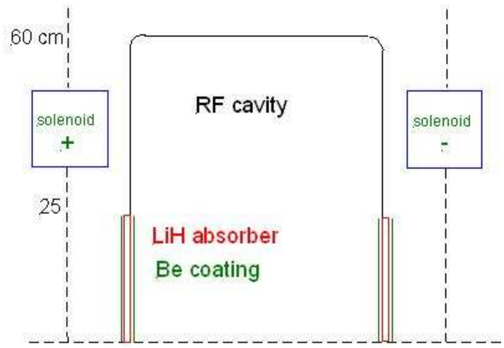

Figure 2. One half-cell of the cooling lattice.

Heating of the LiH absorbers from the beam and *rf* fields need to be carefully understood [5]. Melting or differential stresses could cause the thin Be layers to come off the LiH. The beam heating comes from dE/dx losses in the material. The maximum expected power deposited in the LiH is 58 W. The power from the cylindrical pillbox *rf* cavity is deposited inside a skin depth of the Be layer facing the cavity. The expected *rf* power loss is 220 W.

The cooling channel reduces the normalized transverse emittance ϵ_{TN} by about a factor of 2. There is no longitudinal cooling in this channel. The channel produces a final value of ϵ_{TN} = 7.1 mm rad. The equilibrium value for a LiH absorber with an 80 cm beta function is about ϵ_{TN}^{eq} 5.5 mm rad.

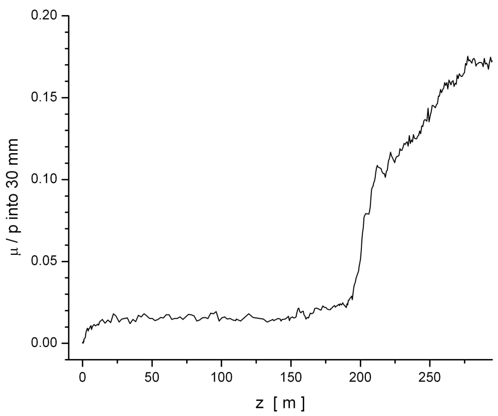

Figure 3. Positive charge muons/proton inside the accelerator acceptance. Plotted data has 100 < p < 300 MeV/c.

Figure 3 shows the number of muons/proton that fit in the accelerator acceptance as a function of distance along the front end. The accelerator transverse normalized acceptance is A_T = 30 mm and normalized longitudinal acceptance is A_L = 150 mm. The total number of muons in the momentum band falls by about 30% in the cooling channel. Decays account for 6%, while most of the remaining 24% are due to particles falling out of the full *rf* buckets. The 80-m-long cooling channel raises the muons/proton in the accelerator acceptance by about a factor of 1.7. The current best value for μ/p is 0.170±0.004. This is the same value obtained in FS2. Thus, we have achieved the identical performance at the entrance to the accelerator as FS2, but with a significantly simpler, shorter, and presumably less expensive channel design. The muons are distributed along a train of ≈ 92 bunches at the end of the channel. The beam is mostly confined transversely inside a radius of 10 cm. Longitudinally the beam is divided into two parts. The useful part is spread out in time, but has a narrow energy spread.

3. DISCUSSION

The front end design presented here gives a muon yield of μ/p = 0.17 into the accelerator acceptance. This is the same yield given for FS2, but with a simplified channel that is estimated to only cost about 53% of the Study 2 channel. In addition both signs of muons are transmitted through the channel, giving a potential gain in useful neutrino flux of a factor of 2. The design suffers in that there is no margin in the number of delivered muons. Many reasonable cost/benefit tradeoffs would cause the yield to drop below the neutrino factory requirements. We are still investigating possible modifications to increase the yield, but it may be ultimately necessary to give up some of the cost savings in order to do this. The other concern is the heating in the LiH absorbers. R&D will be necessary to see if the baseline design is acceptable. Fortunately we have several modified absorber designs that should have better thermal properties and which give only slightly worse muon yields.

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